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Influence of the liver vascular distribution on its overall mechanical behavior: A first approach to multiscale fluid-structure homogenization

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ABSTRACT

Medical applications require the numerical models to be both precise and quickly computed. In the context of liver surgery, this study aims to develop a homogenized mechanical model of the liver accounting for both hepatic tissue properties and macroscopic level blood flow impact. For this, a fluid analysis is carried out to simulate the blood flow inside the liver vessels and extract the pressure on the liver vascularization walls. This pressure is then integrated through a homogenization study, based first on alternative Eshelby type approach, then through a Mori-Tanaka scheme to compute the equivalent material rigidity. Once the equivalent mechanical properties identified, they are integrated into the macroscopic liver model, allowing a light quickly computed model integrating the underlying physics relying on the blood flow mechanical impact.

1. Introduction

In the context of soft tissue surgery, numerical models have the advantages of providing information that will help all people in need of predictive tools to bridge the physiological biology and solid physics. More specifically, in the context of mini-invasive tumor surgery of the liver, real time augmented reality provide the surgeon with a lot of information in 3D that can help him making the right surgical decisions. Numerical models can now provide pre and per-operation 3D real time data [1] computed quickly but lack precision. Although parametric approaches like Proper Generalized Decomposition (PGD) Method [2] allow providing a real-time response, they still require integrating simplified mechanical behaviors. To solve this problem, a multilevel homogenization is used, based on the results obtained first by a full model on a real patient liver and blood vessels geometry. Once the impact of those microstructures identified [3], a homogenized numerical model is built providing the precise deformations and displacements. Finally, the mechanical response of the complete model is compared using indentation tests to available literature reference [4] to identify the mechanical impact of the blood pressure. The results of both studies, the identification of the blood pressure field on a macroscopic level, and the mechanical impact of a given pressure on liver material, are coupled to build a light and precise model of the liver allowing real-time mechanical simulations.

2. Model development

2.1. Fluid analysis

Since the works of Kerdok [5], it is well known that the liver mechanical properties are impacted by the blood flow. Until now, this impact was merged with the hepatic tissue mechanical behavior, through hyperelasticity or viscoelasticity constitutive laws. However, this integration remains approximated as it is within the solid tissue definition itself and cannot properly integrate the impact of large vessels. In order to determine the macroscopic mechanical impact of the blood flow inside the liver, a fluid-structure simulation was run on the vascularization geometries of a patient to get the pressure induced by the blood flow on their walls combined with a multilayer homogenization of the mechanical properties. The initial geometries are extracted from CT-Scan out of the IRCAD (Research Institute against digestive apparatus cancer) open database [6]. The model is based on the mechanical properties of each material extracted from experimental tests through non-invasive techniques [7,8] and literature data indicating an average of 10 mm Hg (1333.22 Pa) pressure in the liver portal flow and 5 mm Hg (666, 61 Pa) in the sub-hepatic vein capillaries. While the liver pressure gradient between the portal vein and the vein cave has few inter-patient variations, the variation of the blood flow fluxis quite important. To adjust the boundary conditions to the

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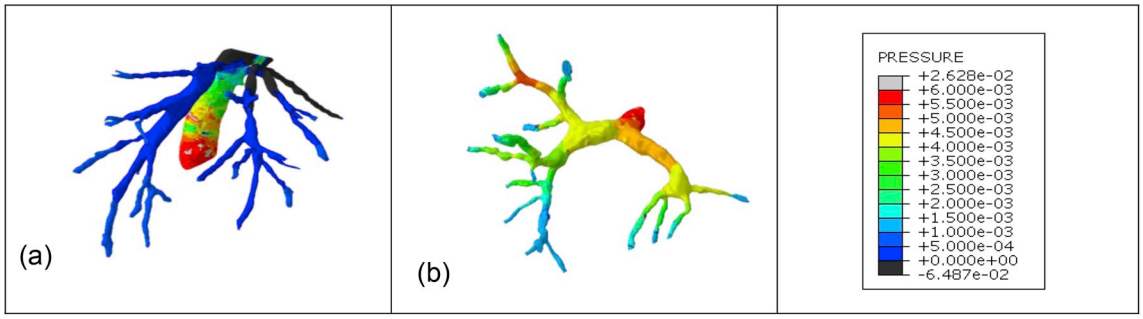

Fig. 1. Blood pressure field on the liver vascularization (MPa) - (a) Vein cave blood field, (b) Portal vein blood field.

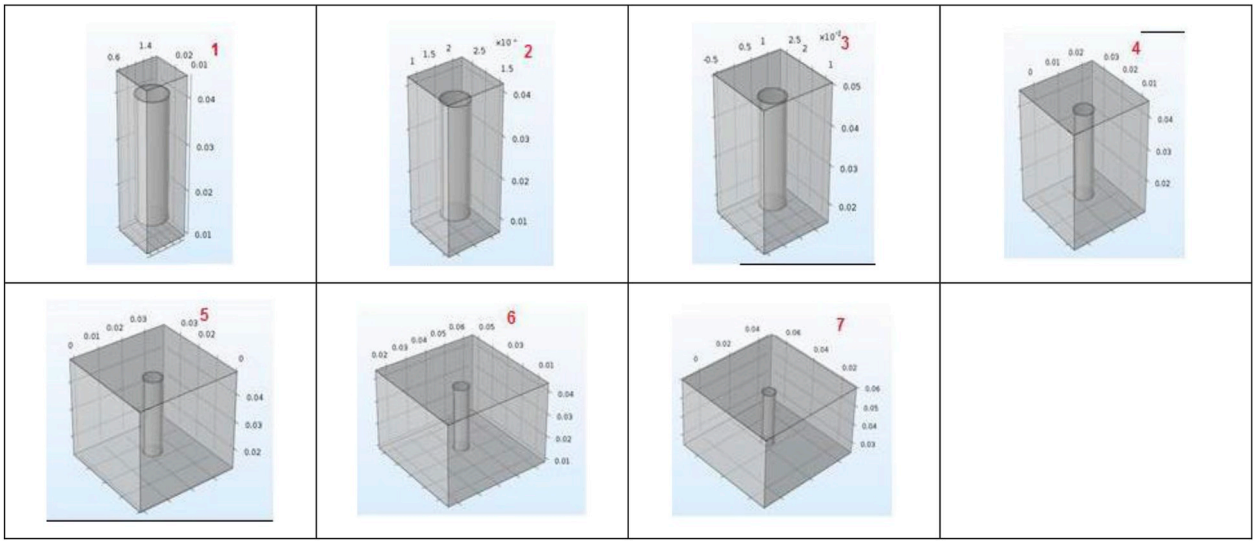

Fig. 2. Seven Prototypes (red numbers) with different size and different insertion (blood vessels) type inside matrix (liver).

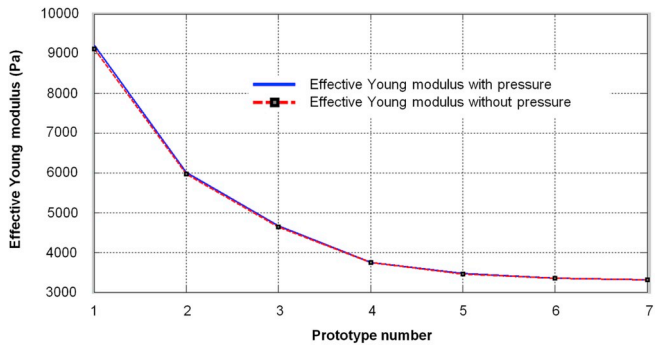

Fig. 3. Equivalent macroscopic Young's modulus for each RVE prototype. Red and blue curve are superimposed.

specific geometry of the patient, simulations were done to fit two parameters being one the vein cave main trunk in-flow and out-flow ratio and the second one the total amount of blood going through the liver. The equilibrium is reach for the vein cave when the flow goes from the liver to the main trunk while keeping the pressure positive on the sub-hepatic vessels. Finally, the portal vein boundary conditions are deduced knowing that it brings around 80% of the liver blood. Fig. 1 presents the pressure fields on the vein cave and portal vein inside the liver for the given geometry. We observe that, for the vein cave, the pressure field is far more important on the main trunk, while for the portal vein it is more concentrated at the entrance.

Those pressure field are then integrated in a full fluid-structure interaction simulation [9]. The results of the fluid-structure interaction study allows to get the mechanical impact of the blood flow on the macroscopic level that needs to be integrated through homogenization into the model of the liver to obtain a precise mechanical behavior being patient dependent.

2.2. Homogenization

Multi-level homogenization is often used to get an estimation of the effective properties of heterogeneous solids [10]. Here, the task of effective properties homogenization is split into a two-level homogenization. We run a local homogenization, in the first place, on the reinforcement together with its interphase layer (the blood vessels, consisting of the vessel wall and the blood running inside, are replaced with their equivalent in homogeneity) to find the equivalent homogenized replacements. These, in interaction with the homogeneous host tissue, are then homogenized using a multiphase cylindrical heterogeneities based on the Eshelby type approach [11] or Generalized Explicit Eshelby-type Estimator (GEEE) approach [12]. GEEE is not only accurate and general enough to cover any ellipsoidal configuration or limit cases thereof, but fast to implement. A second homogenization is then conducted on the homogeneous replacements within the host matrix (liver) to find the macroscopic effective properties of the heterogeneous solid. For the host tissue, a Mori-Tanaka scheme was used for the second level of homogenization.

3. Results and discussion

Simulations have been performed to estimate the equivalent macroscopic Young's modulus. The liver material is considered with a Young modulus of 3 KPa and Poisson ratio 0.3 with the density

1000 kg/mˆ3. The vascularization is considered with a Young modulus of 620 kPa and Poisson ratio 0.3 with the density 1000 kg/mˆ3. In order to account for the influence of blood vessel's pressure on the equivalent Young modulus, all simulations were performed twice; once with an applied internal pressure of 15998.5 Pa (corresponding to an average blood pressure of 120 mm Hg) and once without internal pressure.

Seven prototypes have been used in order to find their equivalent Elastic modulus (see Fig. 2). For each prototype, three different simulations have been performed: (i) with applied external stresses and pressure inside the vessel, (ii) with applied external stresses but without internal pressure to see if pressure is playing a role on the equivalent elastic modulus, and (iii) with applied external strain to find the suitable RVE size for the system.

Fig. 3 displays the macroscopic equivalent Young Modulus calculated for each of the seven prototypes using FEM, under strain loading with and without pressure inside the vessel. The first observation is that with or without applied constant pressure inside the tube for the different RVE cases, under the assumption of linear elastic behavior, it does not change the equivalent Young's modulus (red and blue curve are superimposed).

However, as the external dimensions of the RVE decrease to be closer to the vascularization tube, equivalent stiffness increases going far away from 3 kPa (being the average base of Young's modulus for the liver) towards higher values as it gets closer to the vascularization (here 9 kPa). We therefore deduce that, for static internal pressure inside the vascularization, the influence is very small from the applied pressure but is mainly due to the stiffness of the vascularization walls. Consequently, in a real patient's liver, the global mechanical behavior of the liver will be influenced by vascularization mainly close to the main vascularization trunks (i.e. the first two or three branches of the trunk) and not far away since this is where the vascularization wall stiffness will be the highest. The homogenized liver Young's modulus should therefore account for the patient's vascularization distribution to be able to predict adequately its true mechanical behavior to implement into the numerical models and obtain precise predictive behaviors.

4. Conclusion

The construction of a numerical model of the liver for surgical application requires both precision and lightness. Applying those conditions to the liver vascularization to build a precise and quick numerical model requires integrating their true mechanical impact without having to compute full fluid-structure interaction for every patient and surgery. Based on a classical liver geometry, an equivalent homogenized model is built. The obtained results allow translating a complex and precise fluid-structure analysis into a homogenized structure with a rigidity variation accounting for the local effects, preserving the model precision, and display both precision and lightness.

References

[1] Hostettler A, Nicolau SA, Forest C, Soler L, Rémond Y. Real time simulation of organ motions induced by breathing: first evaluation on patient data. Biomed sim. LNCS 4072. 3rd int. Symp. ISBMS. Zurich, Switzerland. 2006. p. 9–18.
[2] Chinesta F, Keunings R, Leygue A. The proper generalized decomposition for advanced numerical simulations. Springer International Publishing; 2014. p. 117.
[3] Kugler M, George D, Nicolau S, Hostettler A, Soler L, Chinesta F, et al. Modèle de la cinématique déformable réelle du foie et de ses vascularisations en vue d'une simulation temps réel lors d'une chirurgie mini-invasive. 7th AVIESANColloquium. 2015. [Montpellier, France].
[4] Kugler M, Hostettler A, Soler L, Borzacchiello D, Chinesta F, George D, et al. Numerical simulation and identification of macroscopic vascularised liver behaviour: case of indentation tests. Bio Med Mater Eng 2017;28:107–11.
[5] Kerdok AE, Ottensmeyer MP, Howe RD. Effects of perfusion on the viscoelastic characteristics of liver. J Biomech 2006;39:2221–31.
[6] "3D-IRCADb 01," IRCAD France. [http://www.ircad.fr/research/3d-ircadb-01/] .
[7] Hostettler A, George D, Rémond Y, Nicolau SA, Soler L, Marescaux J. Bulk modulus and volume variation measurement of the liver and the kidneys in vivo using abdominal kinetics during free breathing. Comput Meth Progr Biomed 2010;100:149–57.
[8] Nierenberger M, George D, Baumgartner D, Rémond Y, Ahzi S, Wolfram R, et al. Towards building a multiscale mechanical model for the prediction of acute subdural hematomas. Eng Syst Des Anal 2012;4:261–6.
[9] Hoarau Y, Kugler M, Soler L, Rémond Y, George D. Blood flow numerical simulation in a realistic liver model : effect of blood pressure on the liver rigidity. 7th int. Conf. Comp. Bioeng. 2017. [Compiègne, France].
[10] Rémond Y, Ahzi S, Baniassadi M, Garmestani H. Applied RVE reconstruction and homogenization of heterogeneous materials. Wiley-ISTE; 2016. p. 206.
[11] Hori M, Nemat-Nasser S. Double-inclusion model and overall moduli of multi-phase composites. Mech Mater 1993;14:189–206.
[12] Nemat-Nasser S, Hori M. Micromechanics: overall properties of heterogeneous materials. Amsterdam: North-Holland; 2013. p. 708.